THE WEATHER OF OTHER PLANETS

by Andrew P. Ingersoll

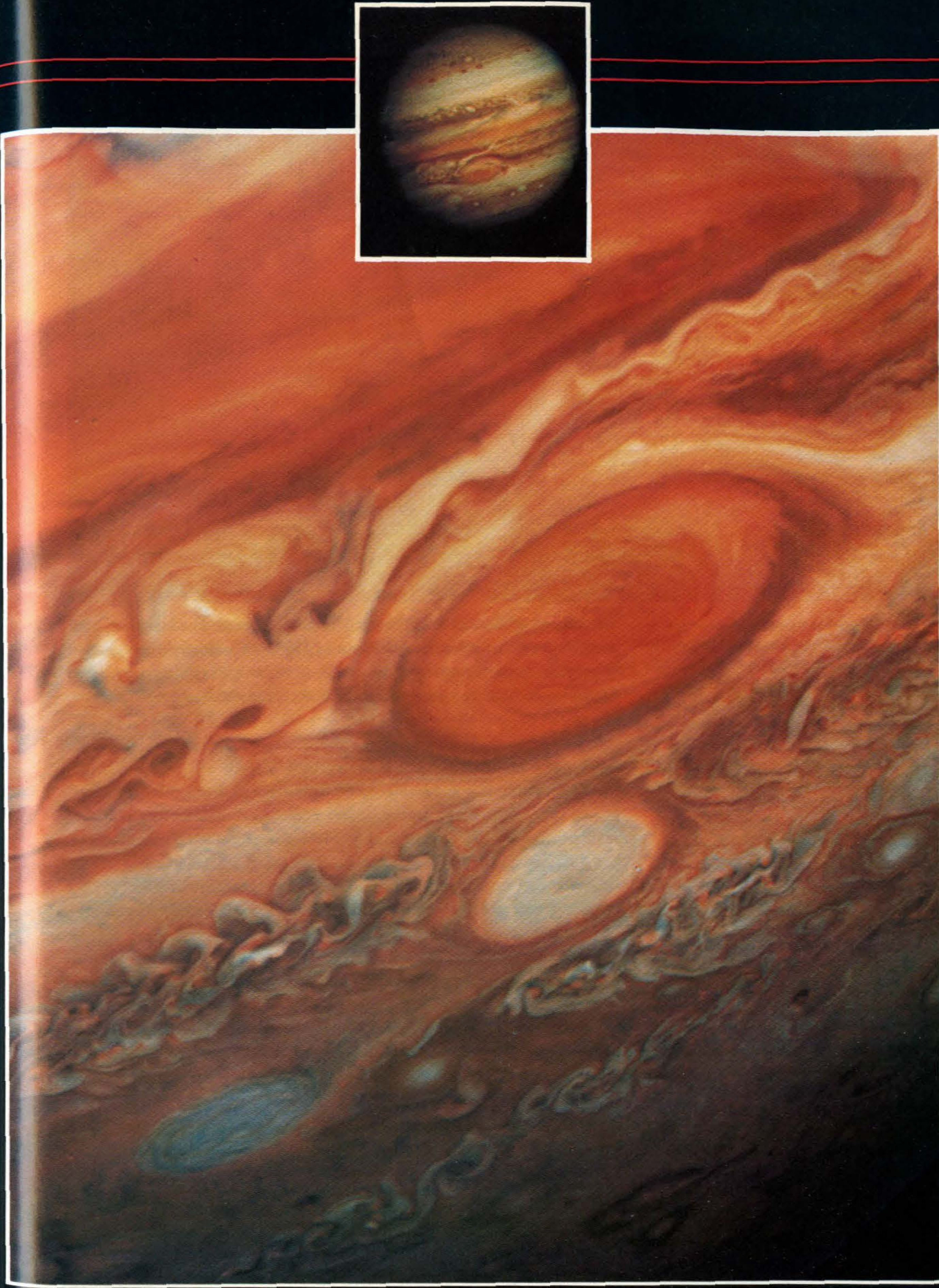
Recent observations from spacecraft and from powerful Earth-based telescopes are providing new information concerning the atmospheres and climatic conditions of other members of the solar system.

Weather is the state of the atmosphere—the wind, temperature, pressure, humidity, precipitation, cloudiness, vapor, and aerosol content—at a given place and time. Climate is the average weather over a period of time, such as during the ice ages or the climate of Mars. The study of weather and climate is called either atmospheric science or meteorology. Weather forecasting is just one aspect of this science, which also includes studying past climates, the climates of other planets, and the origin and evolution of planetary atmospheres.

There are practical reasons for including remote planets and past climates in this study. Scientists know from the geologic record that the climate of the Earth has changed considerably. Tropical plants once grew at high latitudes in Greenland and Antarctica. Many species of plants and animals became extinct as a result of climate change. Glaciers covered half of North America just 20,000 years ago, which is just a tick of the geologic clock—equivalent to 0.4 second if the Earth were one day old. It is also known that human beings are accelerating the process of climatic change, by adding carbon dioxide, aerosols, and other chemicals to the atmosphere, and by altering the soil, water, and vegetation at the Earth's surface. To assess the climatic impact of human activities, it is useful to understand the extreme cases. That is one way in which other planets and ancient geologic records are interesting.

Studying the weather and climates of other planets also sheds light on the origin of life. Life as it exists on the Earth requires certain elements, principally carbon (C), hydrogen (H), oxygen (O), and nitrogen (N). These are present in all planetary atmospheres in simple compounds such as methane (CH_4), water (H_2O), carbon dioxide (CO_2), and ammonia (NH_3). Liquid water is also a requirement, which implies temperatures somewhere between the freezing and boiling points of water (0°–100° C, 32°–212° F). Such temperatures are found at some times and places on all the planets from Mercury to Neptune but usually not with liquid water present.

Another requirement for the development of life may be peace and quiet. The lifetimes of fragile organic molecules must have been short in the lakes



NASA

The northern limb of Mercury was photographed from the Mariner 10 spacecraft at a distance of 78,800 kilometers (49,000 miles). Mercury lacks an atmosphere, and so its weather depends entirely on whether it is day or night. At noon on the planet's Equator temperatures rise to 625 K (665° F), and at night they fall to 100 K (−280° F). On the preceding page is a view of Jupiter's Great Red Spot taken from Voyager 2 at a distance of 6 million kilometers (3,730,000 miles).

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(Overleaf) Photos, Jet Propulsion Laboratory/NASA

and seas of primordial Earth. Such lifetimes would be much shorter in a deep atmosphere such as that of Venus or Jupiter, where winds carry molecules down to sterilizing temperatures or up to destructive ultraviolet light. Favorable climatic conditions apparently occurred simultaneously on only one planet in our solar system—Earth.

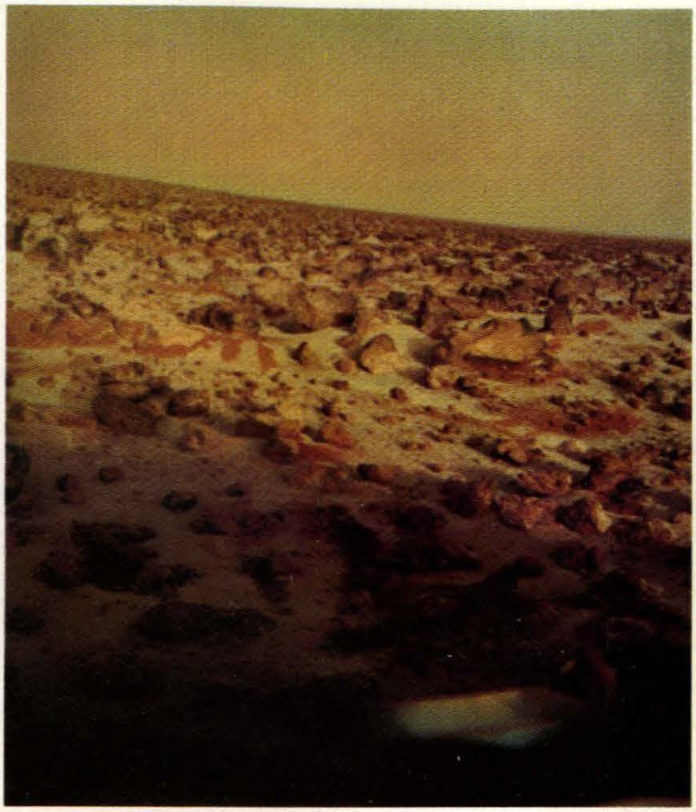
A weather forecast for the solar system

To imagine what it would be like on the surface or in the clouds of another planet, one might first consider airless bodies such as Mercury and the Moon; then Mars, which has an atmosphere 1% as massive as the Earth's; and then Saturn's moon Titan, Venus, and the gas-giant planets, all of which have massive atmospheres. In so doing it soon becomes obvious that the characteristics of an atmosphere make a significant difference in controlling surface conditions.

For Mercury the "weather" depends entirely on whether it is day or night. At noon on the planet's Equator temperatures soar to 625 degrees Kelvin (625 K), about 665° F. At night temperatures plunge to 100 K (−280° F). One complete day lasts for 176 Earth days because Mercury rotates so slowly. These large temperature changes are regular and predictable.

The Moon's "weather" is only slightly less harsh. The maximum daytime temperature is 380 K (225° F), which is colder than on Mercury because the Moon is farther from the Sun. The 120 K (−245° F) nighttime temperature is warmer than on Mercury. This is because the lunar day is shorter (28 Earth days) and the surface has less time to cool off.

Photos, NASA



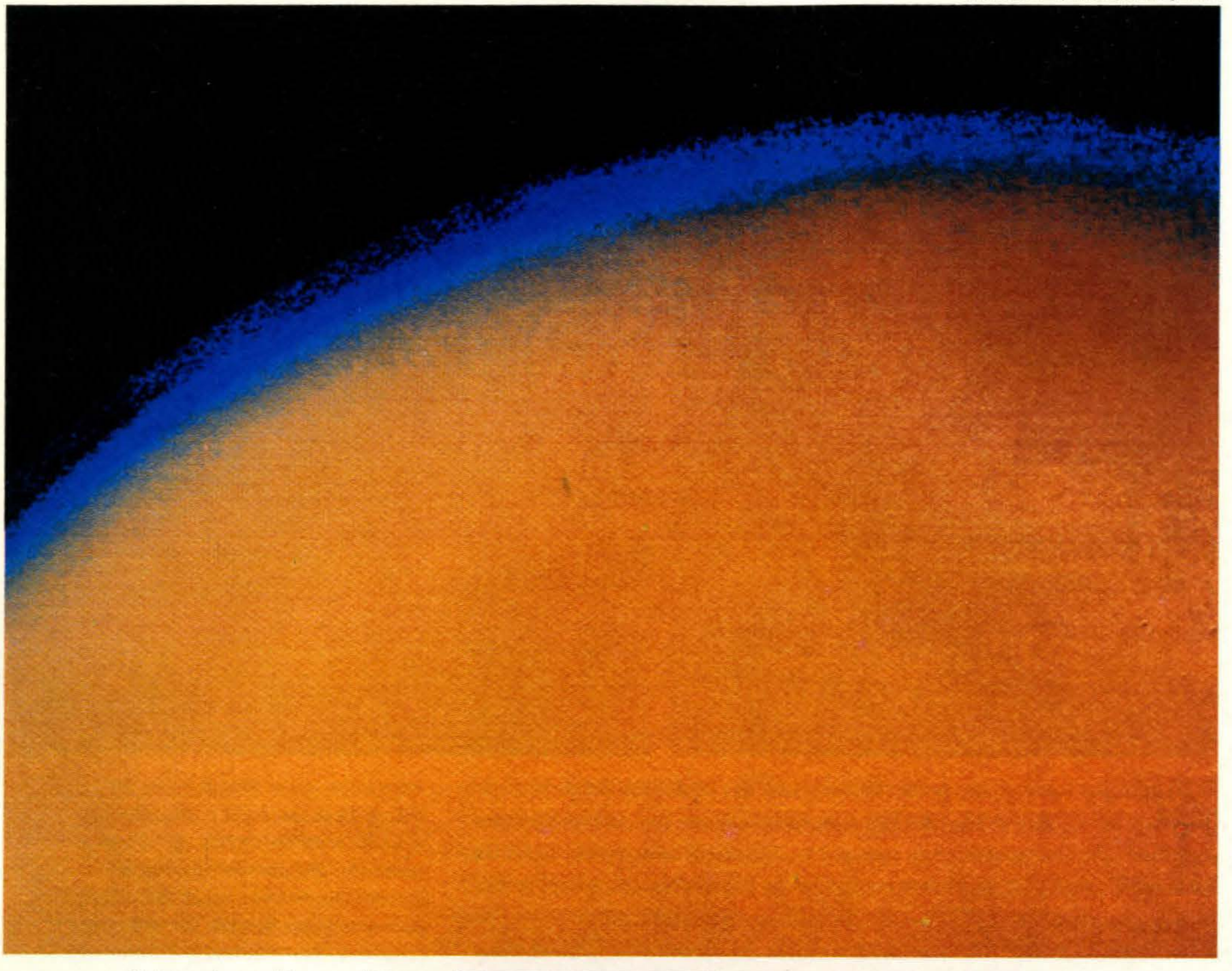
The temperature changes on Mercury and the Moon are large because they lack atmospheres. The Earth's atmosphere stores the daily solar input with only a modest temperature rise, and it continually transports heat from hot regions to cold. Without an atmosphere the Earth's climate would be like that of the Moon.

On Mars as of early 1983 it is late autumn at the second Viking Lander site (latitude 48° N). The Martian day is only 37 minutes longer than that on the Earth. Nights are cold; the minimum temperatures are approximately 150 K (−190° F), which is cold enough to condense both water vapor and carbon dioxide from the atmosphere. Indeed, ice clouds and fog are forecast for this season. Autumn is also a stormy season on Mars. Winds in the atmosphere above the Viking Landers reach hurricane force (116 km/h; 72 mph), and global dust storms take place. The dust will obscure the Sun and will take several weeks to settle. Near the Equator daytime highs range up to a comfortable 280 K (45° F), warm enough to melt ice. But there is no water or ice on that part of the planet; it all lies trapped at the poles. Most of Mars is literally dry as dust.

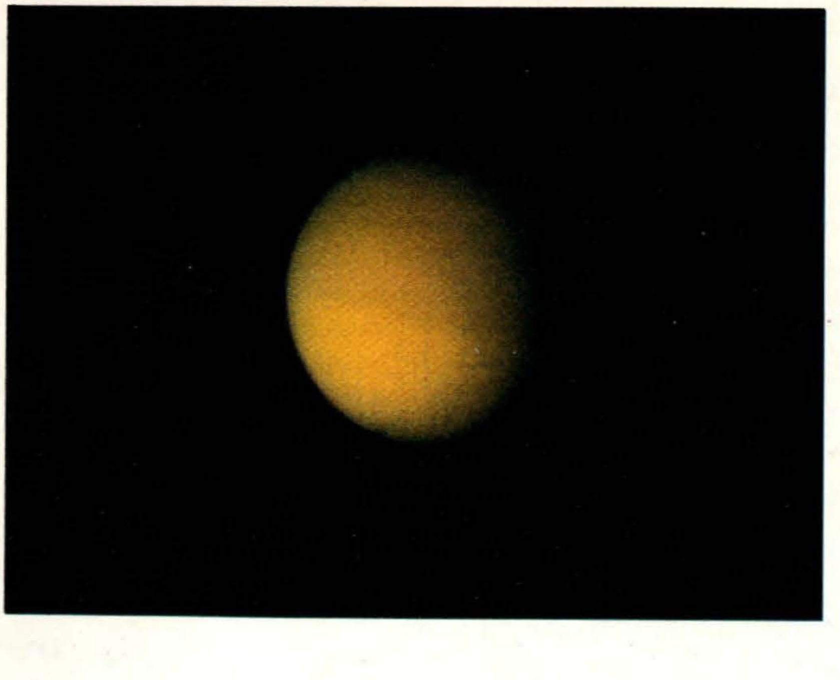
On Titan, Saturn's largest moon, it is early spring in the northern hemisphere. Indeed, spring will last until 1987, for Titan's year is the same as Saturn's, about 29 Earth years. The weather forecast is for smog—a fine rain of black carbon compounds that are created by sunlight in the clouds 160 kilometers (100 miles) overhead. At the surface the temperature is about 90 K (−295° F), and it varies by only a fraction of a degree from day to night. The mass of the atmosphere is about ten times that on Earth.

Above left, Mars as seen from the Viking 2 spacecraft at a distance of 419,000 kilometers (260,355 miles) reveals bright plumes of water ice extending northwest from the volcano Ascreaus Mons. On the surface of Mars (above) a very thin layer of water ice coats the rocks and soil around the Utopia Planitia landing site of the Viking 2 lander.

Photos, Jet Propulsion Laboratory/NASA



Color-enhanced image of Titan, Saturn's largest moon (above), was taken from Voyager 1 at a distance of 435,000 kilometers (270,000 miles). It shows that Titan is covered with a layer of haze, which consists mainly of fine carbon compounds and which merges with a darker cloud layer at the north pole. At the right the true colors of Titan's haze are seen from Voyager 1 at a distance of 4.5 million kilometers (2.8 million miles).



Other characteristics of Titan are unknown. These include the amount of sunlight reaching the ground and even if there is a ground. The planet may be covered by a liquid methane ocean or a frozen layer of ice. Methane raindrops may fall, and methane rivers may flow, but no one yet can be sure.

Venus is another cloud-covered planet. With an atmosphere one hundred times more massive than that of the Earth, it experiences little daily variation in temperature. At the ground there are gentle winds (a few mph) and red-hot temperatures, about 730 K (855° F). In the clouds at an altitude of 55 kilometers (35 miles) temperatures are comfortable—about 295 K (72° F). Winds there are strong but steady. In a balloon at that altitude one would circle the planet every four days. The balloon would be enveloped in a bright mist of sulfuric acid drops, and passengers would barely be able to make out another balloon floating one kilometer away.

On Jupiter, Saturn, Uranus, or Neptune balloons must be used. These planets have no surfaces and therefore are called the gas-giant planets. A person floating at the edge of Jupiter's Great Red Spot or in one of the wide jet streams that circle that planet would be moving at a speed of 240 km/h (150 mph). The forecast for the Great Red Spot and other storms is that they will persist indefinitely, despite their high peripheral winds and intense small-scale motions. Indeed, this persistence is one of the mysteries about the giant planets. It may be due to the great depth of their atmospheres, but no one knows.

Evolution of planetary atmospheres

The kinds of matter one finds in the inner and outer parts of the solar system are very different. In the outer solar system hydrogen (H) is the most abundant element. It binds to other chemically active elements to form compounds such as CH_4, NH_3, and H_2O. The remaining hydrogen binds to itself to form molecular hydrogen (H_2). These compounds and the inert gas helium are the major constituents of the four giant planets and their atmospheres. In the inner solar system oxygen (O) is the most abundant element. It combines with metals to form metallic oxides (rocks), which are the major bulk constituents of the four terrestrial planets. It also combines with carbon to form CO_2, which is the major atmospheric constituent of Mars and Venus and an important compound on Earth. Hydrogen is present on the terrestrial planets largely in combination with oxygen and is not a major bulk constituent of the inner solar system.

These basic differences between the inner and outer solar system probably are the result of the high temperatures close to the early Sun. Hydrogen was the most abundant element in the primordial cloud of dust and gas that eventually contracted to form the Sun and planets. This inference is based on the facts that the Sun is mostly hydrogen and that most of the solar system's mass is in the Sun. The lightest elements, including hydrogen and helium, were largely driven out of the inner solar system by the high initial temperatures. The heavier dust grains remained closer to the Sun to form the rocky inner planets.

There is evidence that the gases now in the atmospheres of Venus, the Earth, and Mars were chemically bound to the solid particles at the time of

Tass/Sovfoto

On the surface of Venus (above), as photographed from the Soviet Venera 14 lander, the planet's massive atmosphere has damped out day-to-night swings of temperature. The cloud-covered surface experiences gentle winds and temperatures of about 730 K (855° F).

formation. If these atmospheres were simply a small remnant of the primordial cloud, then their composition should resemble that cloud. In particular, the noble gases neon, argon, krypton, and xenon should be present in approximately equal parts with carbon dioxide, water, and nitrogen. However, the noble gases cannot form chemical bonds, and they are rare in the inner solar system. They were presumably swept away with hydrogen when the Sun was forming. Later internal heating of the inner planets may have released the chemically bound gases, which then became the atmospheres and (for the Earth) the oceans of those planets.

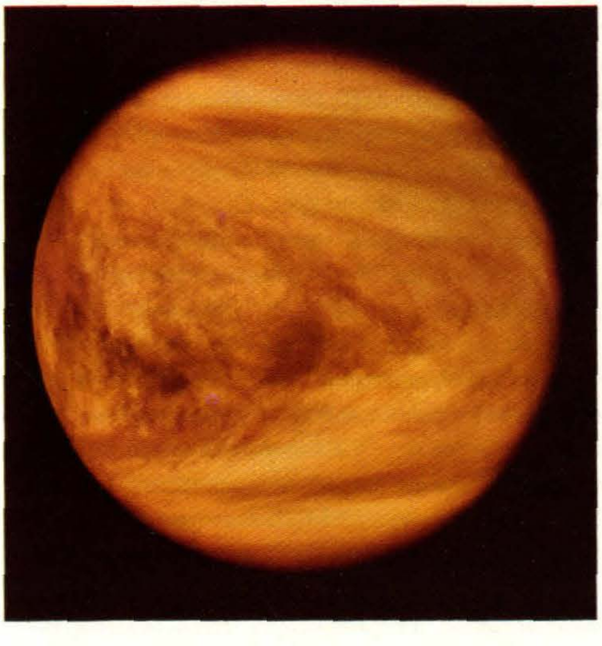
It was known before the space program that the Earth had outgassed huge amounts of water and carbon dioxide. The water is mostly in the

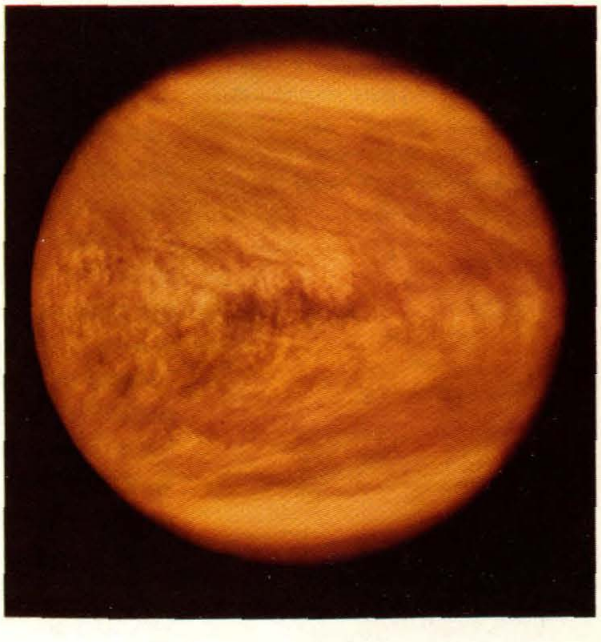
Photos, NASA

oceans, which have a mass equal to about 300 Earth-atmospheres. The carbon dioxide is now mostly in limestone rocks (calcium carbonate—$CaCO_3$), which formed as ocean sediments from dissolved CO_2 and calcium salts. The total mass of CO_2 is uncertain because some of the limestone has been buried by drifing continents, but estimates range from 40 to 100 atmospheres. The atmosphere itself is approximately one-fifth molecular oxygen (O_2) and four-fifths molecular nitrogen (N_2).

Venus has about 100 Earth-atmospheres of CO_2, but it all resides in the massive atmosphere. The high temperatures on Venus do not allow limestone to form. Venus has about two Earth-atmospheres of N_2, which is also in the atmosphere. Water is a trace constituent of the atmosphere, and there

Ultraviolet photographs of the clouds over Venus (opposite page, bottom and below) were taken from the Pioneer Venus orbiter over a period of 38 hours at intervals of 9½ hours, 4½ hours, and 24 hours (left to right). The clouds of Venus circle the planet completely once every four days.





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Mosaic of the surface of Mars consists of photographs taken from the Viking 1 orbiter on four separate revolutions. The well-defined channels suggest that the now dry and frozen surface once contained rivers of liquid water.

are no oceans. But recent spacecraft results indicate that large amounts of water have been lost from Venus. The evidence is that the hydrogen of Venus is heavier; that is, it is richer in the heavy isotope deuterium (^2H) than is the hydrogen on Earth. This fact implies that large amounts of hydrogen were lost by evaporation into space, since evaporation favors the lighter isotope and leaves more of the heavier variety behind.

Thus Venus and the Earth seem to have started with approximately the same inventory of volatile compounds. This is not too surprising, since the two planets are roughly of the same size and density. Differences arose later as a result of their different positions in orbit around the Sun. Venus, being closer to the Sun, was, and still is, hotter than the Earth. Therefore, water and carbon dioxide remained in the atmosphere of Venus, whereas on the Earth both substances condensed into the oceans and ocean sediments. Sunlight could have converted the massive water vapor atmosphere of primordial Venus into hydrogen and oxygen. The former evaporated into space, and the latter combined with surface materials to form oxides.

Mercury and Mars represent more extreme examples of Earthlike planets that are either too near or too far from the Sun. At Mercury's orbit gases apparently could not bind to the hot dust grains or could not stay bound to the hot planet once it had formed. Thus Mercury has no appreciable atmosphere. Mars has a thin atmosphere that is mostly carbon dioxide. The low temperatures there limit the amount of water and carbon dioxide that the atmosphere can hold. To a large extent these substances are frozen out at the Martian poles.

Nitrogen and the noble gases provide additional information, some of which seems to contradict the theories that have been discussed above. The low abundance of molecular nitrogen (N_2) on Mars seems to imply either less outgassing of the interior or less initial binding of gas to the dust grains from which the planet formed. The first explanation suggests that Mars had an internal history that differed from that of the Earth and Venus. Yet all three planets resemble each other in bulk properties. The second explanation suggests that less gas was bound to the solid material at the orbit of Mars than at the orbits of either the Earth or Venus. Yet high temperatures on the early Sun imply that more gases would be bound at Mars. The resolution of this conflict probably involves some currently overlooked aspect of planetary evolution.

Saturn's largest moon, Titan, provides a good example of atmospheric evolution in the outer solar system. Neptune's largest moon, Triton, and the ninth planet, Pluto, may provide similar examples, but little is known about these objects. All have weak gravity and cannot retain H_2 gas in their atmospheres. Titan's atmosphere is mostly N_2, as is the Earth's. Carbon is present as CH_4 and as more complex hydrogen-carbon compounds that form the black cloud particles. Water is frozen out of Titan's atmosphere. This last fact accounts for the almost complete absence of oxygen in any form, although both carbon monoxide (CO) and CO_2 have been detected in small quantities.

Titan may, in fact, be a frozen version of the early Earth, which according to some theories once had abundant CH_4 and NH_3 in its atmosphere. Sunlight gradually liberated hydrogen, which escaped into space. Nitrogen accumulated in the atmosphere as N_2. On Earth, with oxygen available as water, the carbon became CO_2. Green plants took CO_2 and water to make carbohydrates and oxygen, which also accumulated in the atmosphere. This evolutionary pathway is apparently blocked on Titan because of the low temperatures. Although temperatures might have been higher when Titan was forming and a climate favorable to life might once have existed, it seems unlikely that life exists on Titan today.

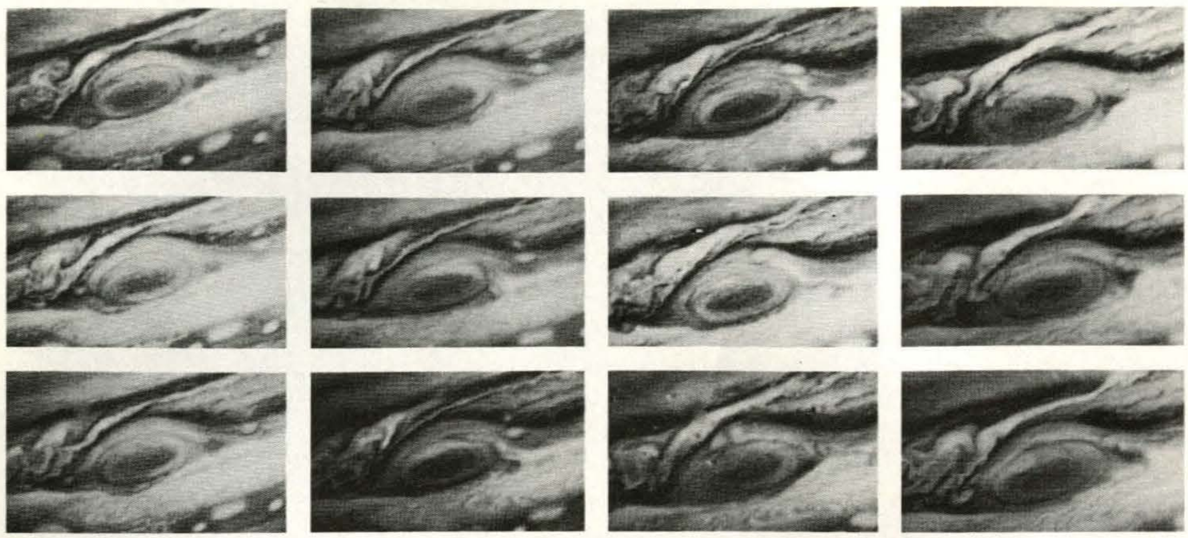
NASA

North polar ice cap on Mars is revealed in photomosaic taken from the Viking 2 orbiter. The translucent streaks of varied tones overlie both the ice and the defrosted layered material and may have been formed by the redistribution of ice and soil particles by the wind. The cap consists of ice formed from water rather than from carbon dioxide, as was previously believed.

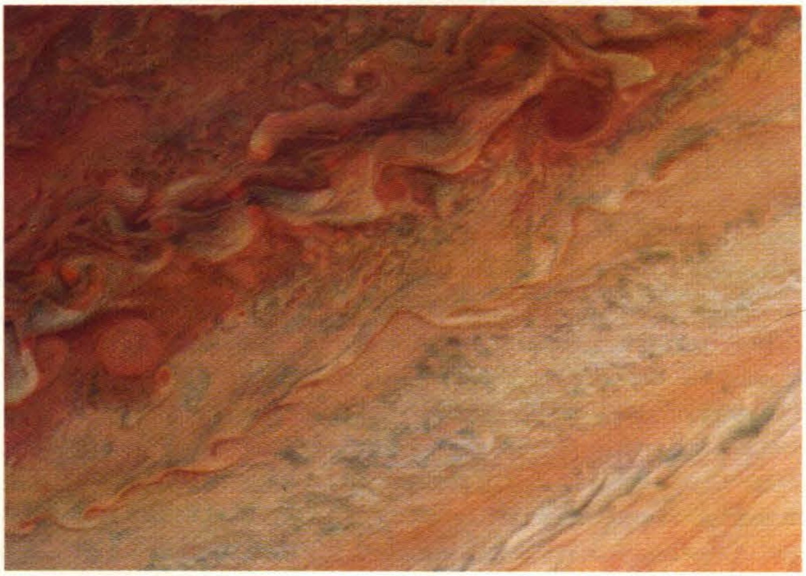
Climate change

The Earth's climate varies on many time scales. The processes that cause the climate to change on these different scales include solar variability, changes in the Earth's orbit, continental drift, erratic behavior of continental glaciers, changes in the deep ocean circulation, biological cycles, and changes in atmospheric composition. In addition, there is a random component to long-term climate just as there is to daily weather. It is possible that the Earth's climate flips spontaneously from one state to another without an obvious external cause.

Photos, Jet Propulsion Laboratory/NASA

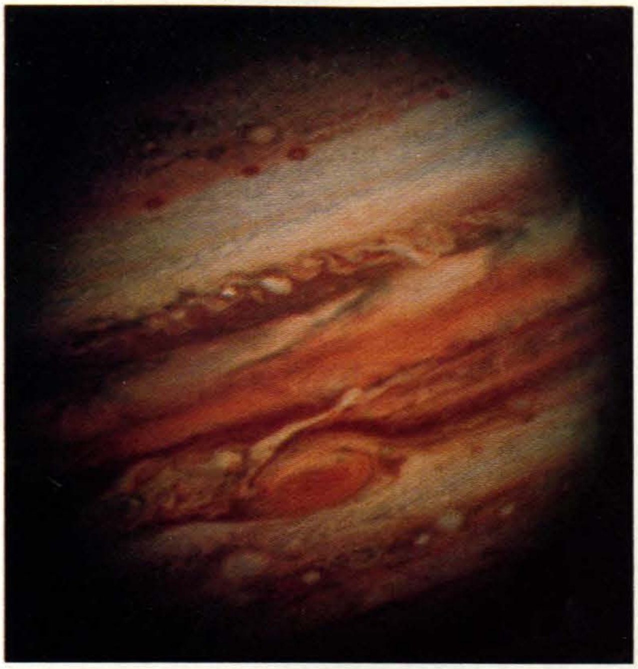


The flow of gaseous fluids circulating around the Great Red Spot on Jupiter is shown in the time-lapse photographs above, taken every odd rotation of the planet; the sequence is from the upper left down each row and ending at the bottom right. Jupiter rotates once every 9 hours 50–55 minutes, while the rotation period of the gases within the Great Red Spot is about six days. At the right is a high-resolution image of the mid-latitudes of Jupiter taken from a distance of 4 million kilometers (2.5 million miles). The pale orange line extending from southwest to northeast (north is at the top) is the north temperate current with wind speeds of about 120 meters per second. Farther north is a weaker jet stream with wind speeds of about 30 meters per second; it is characterized by wave patterns and cloud features that rotate in a clockwise manner.



The history of the Earth's climate is recorded in sediments. In some places the geologic record goes back more than 1,000,000,000 years. One finds evidence of both warm climates and cold climates, but generally the former last longer than the latter. For example, the dinosaurs lived on an unglaciated Earth for more than 100 million years. A slow cooling has occurred during the last 70 million years. For the last few million years polar ice sheets have advanced and retreated across the Earth's surface at intervals of 20,000 to 100,000 years. The most recent advance peaked 20,000 years before the present time and was followed by a rapid retreat that culminated in a warm interglacial period from 5,000 to 7,000 years ago. Since then the climate has become cooler, with minor advances and retreats every few hundred years. During the last hundred years there has been a slight warming.

Photos. Jet Propulsion Laboratory/NASA



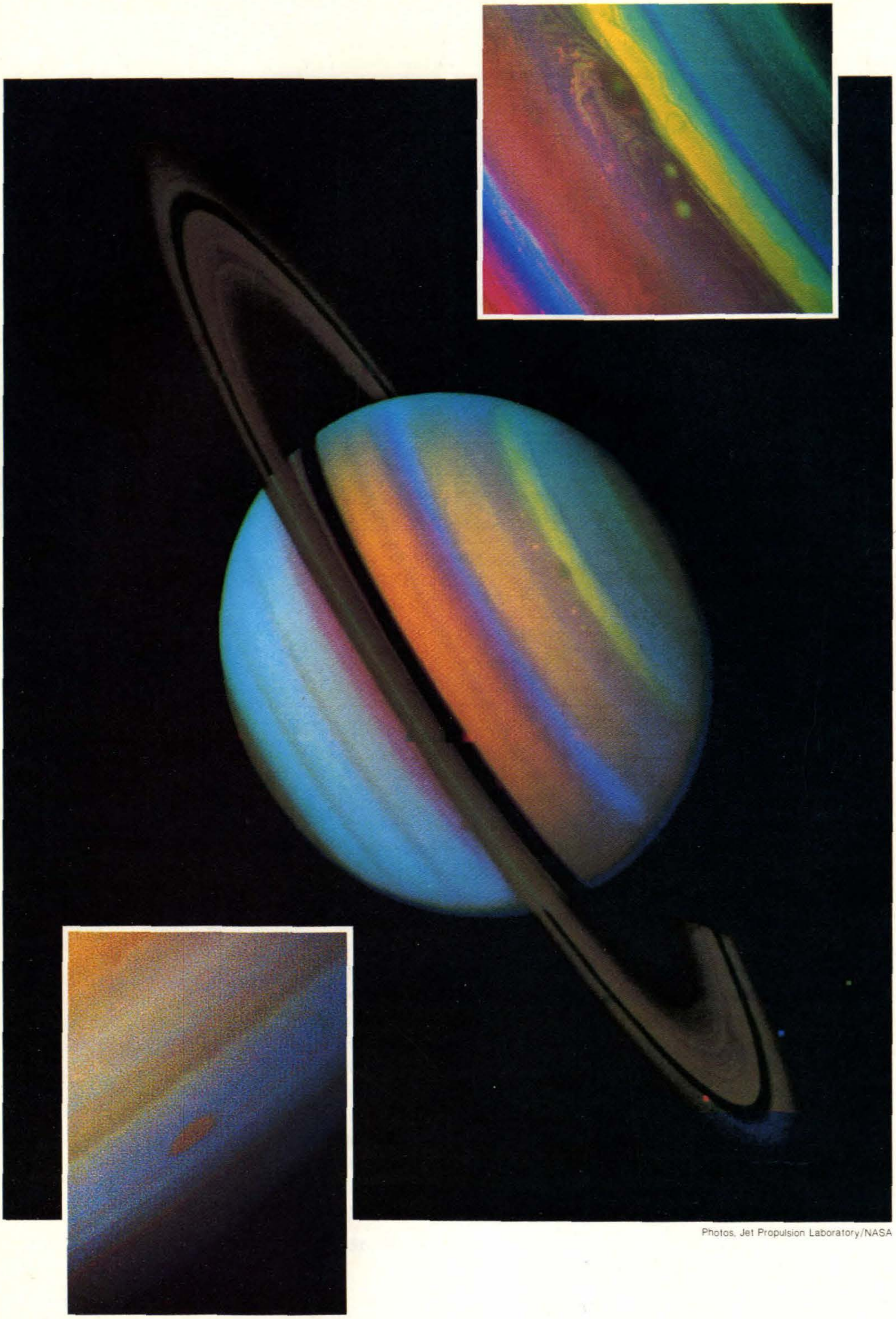
Changes in the atmosphere of Jupiter are revealed by photographs taken about four months apart. The photograph on the left was taken from Voyager 1 on January 24, 1979, from a distance of 40 million kilometers (25 million miles); on the right is a picture from Voyager 2 on May 9, 1979, from 46.3 million kilometers (28.7 million miles). One of the white ovals located below and left of the Great Red Spot in January had drifted 60 degrees eastward (right) by May, while the bright tongue extending upward from the red spot is interacting with a thin bright cloud that had traveled twice around Jupiter during the four months. The satellite Ganymede is visible at the bottom of the Voyager 1 picture.

Mars and Venus provide other examples of climate variability. The ancient riverbeds of Mars are perhaps the most interesting, since Mars today is dry and frozen. The Sun's lower output in the past only complicates the picture. One possibility is that the atmospheric composition of Mars has changed. An atmosphere with one hundred times more CO_2 than at present could trap the outgoing infrared radiation and warm the surface, allowing liquid water to exist. But accounting for the disappearance of this massive atmosphere of carbon dioxide is a problem: Why did it go and where is the CO_2 now?

By trapping the outgoing infrared radiation, the massive CO_2 atmosphere of Venus maintains the surface at a level hundreds of degrees hotter than a hypothetical airless body at the same distance from the Sun. The sulfuric acid clouds of Venus have two effects—trapping the outgoing infrared radiation and reflecting the incoming solar radiation. The former process leads to a net warming and the latter to a net cooling. On the Earth volcanic aerosols that linger in the stratosphere also contain sulfuric acid. These aerosols cool the Earth, their reflective properties outweighing their effect on infrared radiation.

Like the Earth Mars also has orbital cycles that are regular and predictable. They are probably the cause of the so-called layered terrain in the planet's polar regions. Each layer may be a deposit of dust and ice laid down during part of each climate cycle. As on the Earth the polar climates are warm when the seasonal tilt is large, because the poles then receive more sunlight during the year.

What will happen in the future? The answer for the Earth depends on the time scale. Recent volcanic activity has loaded the Earth's atmosphere with sulfuric acid particles. Therefore, for the next year or so there may be a small global cooling. But averaged over the next hundred years there will be



Photos, Jet Propulsion Laboratory/NASA

global warming as a result of increased CO_2 in the atmosphere. If people find ways to avoid burning coal and oil and thereby releasing the CO_2 into the atmosphere, this situation will not come to pass. Finally, over approximately the next 10,000 years the orbital cycles will be driving the Earth into another ice age.

Predictability of the weather

On the Earth it is difficult to forecast the weather more than a few days ahead. In the Northern Hemisphere one can predict with certainty that July will be warmer than January, but it is impossible to predict in January that July 4 will be warmer than July 5. Obviously there is room for improvement, which may be achieved by such means as gathering more weather data and using larger computers. But how much improvement can be expected for a given amount of extra effort? To what extent is atmospheric unpredictability simply something that must be lived with?

The other planets provide some insight in regard to these questions. It appears that the weather on some planets is more predictable than on others. In fact the Earth may have the most unpredictable weather in the solar system. This statement is based on the observed regularity and longevity of flow patterns in other planetary atmospheres. It is surprising that this is the case, since the Earth's atmosphere is neither the least massive nor the most massive, and the Earth's radius, gravity, rate of rotation, distance from the Sun, and average temperature are all intermediate compared with other planets.

The Viking Landers provided a good look at Martian weather. The first data were for the summer season, and it was soon obvious that summer weather on Mars is dull. The variations of wind and temperature are quite predictable and follow a diurnal cycle. As discussed earlier, this diurnal regularity is a general property of planets with thin atmospheres or no atmospheres at all.

Later in the Viking mission the weather became somewhat more variable. On both the Earth and Mars winter is the stormiest season. The storms are driven by the large thermal contrast between the cold winter pole and the warm Equator. The storms on Earth have lifetimes of several days. Old storms are constantly replaced by new ones, which grow unpredictably from small fluctuations. The storms on Mars are more periodic and regular. Wind, temperature, and pressure fluctuations at the Viking lander site are wavelike with a period of about three days. The storms on Mars are apparently less turbulent than those on the Earth. This difference may be due to the more rapid damping of temperature fluctuations in the thin Martian atmosphere. Generally in laboratory fluids the degree of turbulence is inversely proportional to the damping, but the application of this result to planetary atmospheres is uncertain.

Based on the above reasoning, massive atmospheres such as those of Venus and Jupiter should be the most turbulent and unpredictable, since energy is stored for a long time and also because irregular fluid motions are not damped out. But something more interesting happens in these atmospheres. The small-scale motions seem to organize themselves into stable

Color-enhanced photograph of Saturn (opposite page, center) reveals bright spots in the planet's north temperate belt. These may be huge convective storms with upwelling from deep within the planet's atmosphere. The distinct differences in color among the cloud belts of the northern hemisphere may be due to variations in haze layers. The southern hemisphere appears bluer than the northern hemisphere because of the increased scattering of sunlight on that area due to the Voyager 1 spacecraft's point of view. At the top is a color-enhanced picture of Saturn's northern hemisphere assembled from images obtained by Voyager 2. Among the most evident features are three spots flowing westward at about 15 meters per second. A unique red oval is shown in the Voyager 1 photograph of Saturn's southern hemisphere, bottom. The difference in color between the oval and the surrounding bluish clouds indicates that the oval contains a substance that absorbs more blue and violet light than do the clouds.

large-scale structures that persist indefinitely, feeding on the energy in the disorganized small-scale flow.

The long-lived ovals in Jupiter's atmosphere are a good example of this organization. These ovals are circulating masses of gaseous fluid ranging in size from less than 1,600 kilometers (1,000 miles) to an east-west distance of about 26,000 kilometers (16,000 miles) for the Great Red Spot. They continue to circulate for years or even for hundreds of years, even though the small-scale eddies nearby have lifetimes of a few days or less. The Great Red Spot, which has existed for more than 300 years, is constantly engulfing small transient spots.

The jet streams on Venus, Jupiter, and Saturn are another example of stable large-scale structures. The upper atmosphere of Venus rotates with a four-day period, moving westward relative to the surface at more than 320 km/h (200 mph). This westward motion is in the same direction but 50 times faster than that of the solid planet. Jupiter and Saturn have multiple jet streams. Each latitude has its own west-to-east rotation, with relative velocities of approximately 480 km/h (300 mph) on Jupiter and 1,600 km/h (1,000 mph) on Saturn. These east-west (zonal) flows coexist with intense small-scale eddies. However, instead of destroying the large-scale structure, the eddies feed additional energy into the zonal flow. This energy transfer has been measured in Jupiter's atmosphere from Voyager images. It appears also to be occurring on Saturn. And it occurs in theoretical models of the Venus atmosphere.

The above processes seem to involve a spontaneous transition from chaos to order, in violation of one of the basic laws of physics. But it is incorrect to think of an eddy that is several hundred miles in diameter as a chaotic structure. Also, several examples of such a transition have been documented elsewhere in nature. This kind of transfer, from eddies to mean flow, seems to sustain atmospheric currents such as the Earth's jet stream, oceanic currents such as the Gulf Stream, and the zonal flows in other planetary atmospheres.

For these undamped planetary flows predictability seems to be related to inertia. The more massive the atmosphere, the more inertia. Therefore, the large-scale zonal flows of Venus, Jupiter, and Saturn are regular and constant in time. The Earth's jet stream is meandering and variable, perhaps because the atmosphere has less inertia. If these speculative ideas are correct, the Earth is in the unpredictable middle range between Mars, where disturbances are rapidly damped, and the more massive atmospheres, where stable flows persist for long periods due to their large inertia.

The lesson for terrestrial weather forecasting is no different from that which has been taught by everyday experience. There is a limit to the predictability of the Earth's weather. Meteorologists may be able to extend their forecasts for a few days, but soon the inherent instability of the Earth's atmosphere will frustrate their efforts. Still, it would be useful to refine the understanding of these limits in order to see where improvement is possible. Studying the weather on other planets is a way to broaden the perspectives of scientists on the Earth and thereby to improve their understanding of the Earth's weather.

NASA

View of the Earth from the Apollo 17 manned spacecraft reveals Africa and Arabia at the top and extends south to Antarctica. Perhaps because the Earth's atmosphere is less massive than those of Venus, Jupiter, and Saturn, the flows of its jet streams are more meandering and variable, and its weather is, consequently, less predictable.

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